Motion Planning Algorithm for a Mobile Robot Suspended by Seven Cables

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***Abstract*— In this paper we present a motion planning algorithm for a mobile robot, suspended by seven cables. We formulate the motion planning algorithm as convex optimization problem. We analyze the robot's statics and kinematics in order to implement them into the motion planning. The robot consists of cable mechanisms and a central body. Each cable mechanism includes a thin cable with a simple gripper at the end, and a dispensing and rolling mechanism. The robot dispenses the cables towards possible grasping points in the surroundings, and then pulls the cables simultaneously in a coordinated manner. Depending on the geometry of the grasping points and the coordinated pulling, the robot can perform stable motion over curved surfaces or around and over obstacles. Simulations results are presented as well as experiments, conducted on a novel underconstrained four cable suspended mobile robot.**

I. INTRODUCTION

Parallel robots have become a large area of interest in the field of robotics. Cable suspended robots are considered parallel robots because they are a closed-loop kinematic chain mechanism with end-effectors that are linked to the base by several independent kinematic chains. Cable Suspended Robots (CSR's) are divided into three subgroups according to the number of cables [1]. Fully constrained cable robots, underconstrained cable robots and point mass cable robots. . The paper introduces an automatic motion planning algorithm for a mobile robot suspended by seven cables. Our previous work describes the novelty of the design of a four cable suspended mobile robot, SpiderBot [2] (Fig. 1).

The robot consists of a central body which is the moving platform and cable mechanisms that maneuver the central body by adjusting the cables lengths. In order to allow the robot to move from one place to another, the robot dispenses cables to new grasping points while disconnecting others , similar to the ability the famous Spider-Man to climb walls. Our SpiderBot moves in a quasi static manner. This way the robot is capable of maneuvering from one stance space to another while maintaining equilibrium. Stance space is defined as the volume that the moving platform can reach while no new grasping points are established. Stride is defined as the phase in which attachment or detachment occurs in order to perform a gait pattern. SpiderBot has two configurations: internal motion inside the stance space and motion from one stance space to another, similar to walking. At the first configuration the robot is attached by only six cables, while at the second configuration the robot has to use its seventh cable for transition from one stance space to another. The robot can operate over a large workspace as it can change its grasping points and cables lengths. The lightweight cables result in a very safe and transportable system.

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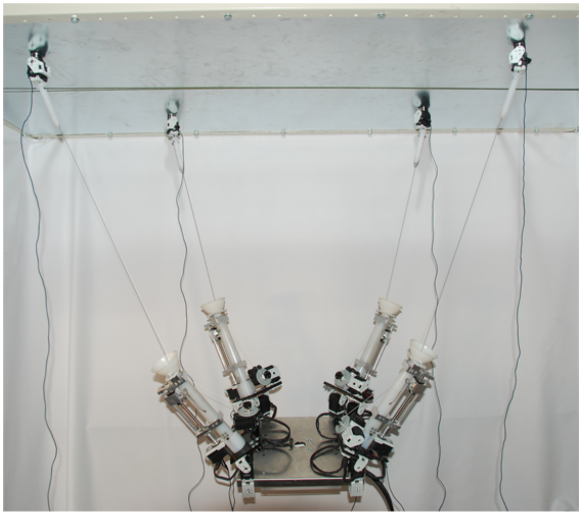

Fig. 1. A prototype of a four cable suspended mobile robot, SpiderBot. The robot is suspended by four cables, the loose cables are conducting cables connected to the gripper enabling the cables to disconnect from the ceiling [2].

Transportable cable-suspended parallel robots have several advantages over the classical parallel robots. First, cables allow incomparable motion range, larger than that obtained from conventional actuators such as hydraulic and pneumatic cylinders. Second, they take up little space when rolled in a spool. Third, cables are lighter than most conventional actuators. They have negligible inertia and are suitable for high acceleration applications. Further, cables are less expensive than hydraulic or pneumatic actuators, and being flexible they provide a natural protection in the case of interference with each other or environmental objects. There are several possible applications for cable-suspended robots: cutting, shaping and finishing, manipulator arm [3], lifting and positioning [4] and flexible fixturing ([5], [6]). Despite these characteristics, there have been relatively few cable robots used in practical applications. Three examples that are currently in use are the Skycam [7], Intelligent Spreader Bar [8] and the Nist RoboCrane [4] -one of the largest application areas of cable-

suspended robots is cargo handling. Fully-constrained cable-suspended robots prevent load sway because of the multiple cables [9].

Most researchers have dealt with issues of workspaces ([10], [11], [1]) and control ([12], [13]) of cable suspended robots. While a number of researchers have developed analytical tools for the analysis of cable suspended robots, for our best knowledge, none have dealt with motion analysis of underconstrained cable robots, capable of walking by attaching and detaching contact points. We present in this work a motion analysis of an underconstrained seven cable robot, capable of walking [14]. The paper is organized as follows: Section II discusses the conceptual design and basic motion of the robot, Section III analyzes the robot's kinematics and statics, Section IV discusses the motion planning algorithm. Section V describes the simulations and experiments that were conducted on a prototype model and Section VI presents some conclusions and future work.

II. Conceptual Design And Basic Motion

In CSR's, consisting of less than six cables, the orientation is coupled with the robots position. In such a case we cannot determine the orientation of the robot by using the kinematic equations only because the solution may not be unique. Therefore we have to also use the static equations in order to determine the orientation of the moving platform [15].In this case the robot converges to equilibrium at the minimum potential energy point. We now analyze the effect of the number of cables on the robot's kinematics. In order to grasp an object with n DoF (Degrees of Freedom), $n+1$ wrenches are needed [16]. In cable suspended robots, gravity acts as an additional cable, therefore in order to constrain n DoF, n+1 cables are needed. As a result, four is the minimal number of cables required for a three dimensional robot to move from one stance space to another. Three cables are required in order to move inside the stance space and the forth cable is required to enable the robot to move from one stance space to another in the Stride phase. If the robot consists of seven cables, six cables for moving inside the stance space and the seventh for the Stride phase, then the kinematics equations are sufficient to determine the position and orientation. Although the analysis shown in this paper is for seven cables robot, the prototype robot shown in Fig. 1, has four cable mechanisms, i.e. it has only three DoF. Each cable mechanism has the same maximum cable length, determined by the required workspace of the robot. The cable mechanism consists of several units: length control unit, semi-passive feedback unit, dispensing unit and attach/detach unit. During the dispensing process the semi-passive feedback unit directs the unit towards the contact location (using its active mode). The dispensing unit fires the cable with the attach/detach unit towards the contact location. When contact is established, the semi-passive feedback unit switches itself to passive mode, and the length control unit pulls the cable until tension is obtained. We now discuss the basic Motion Pattern. Motion consists of six basic steps, shown in Fig. 2. At the first step (Fig. 2(a)) the robot is connected to the surroundings by 3 cables, and the fourth cable remains detached. Under the effect of gravity, the robot is now at equilibrium, determined by the contact points and the cables lengths. At the second stage (Fig. 2(b)), the robot changes its internal configuration by adjusting the cables lengths. The robot then dispenses the fourth currently unattached cable which constructs a new contact point (Fig. 2(c)). The length of the additional cable is large enough so that it does not change the robot configuration. This is accomplished by maintaining the original cables under tension while the fourth cable is kept loose. The robot then releases the tension from the third cable while maintaining its position (Fig. 2(d)). The third cable is then disconnected (Fig. 2(e)). Now, the robot changes its internal configuration by changing the cables' lengths and converges to a new equilibrium (Fig. 2(f)). Motion is then repeated from step one based on the new configuration.

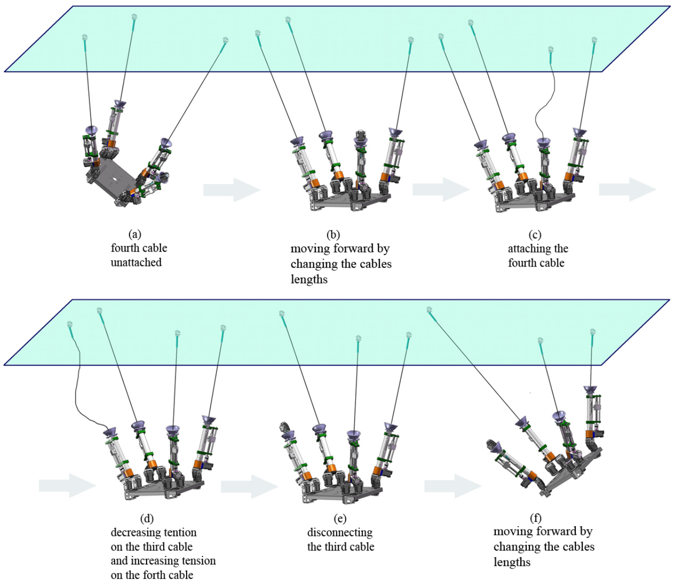

Fig. 2. Six basic steps of motion of the mobile cable suspended robot, SpiderBot.

III. Kinematics And Statics Analysis

This section describes the analytical model for the robots kinematics and statics. The robot moves in a quasi-static manner, maintaining equilibrium configuration at every instance. We define a world coordinate frame F_w with origin O_w and directonal vectors w_x, w_y, w_z (Fig. 3). We attach a coordinate frame F_b to the moving platform of the robot. The origin O_b of frame F_b is located at the center of mass of the moving platform, and the directional vectors b_x, b_y, b_z are shown in Figure 3. The rotation matrix R represent transformation of vectors from F_b to F_w . $R \in SO(3)$ is parameterized by the spatial rotations sequence of roll, pitch and yaw angles, ϕ about w_z, θ about w_y and ψ about w_x.

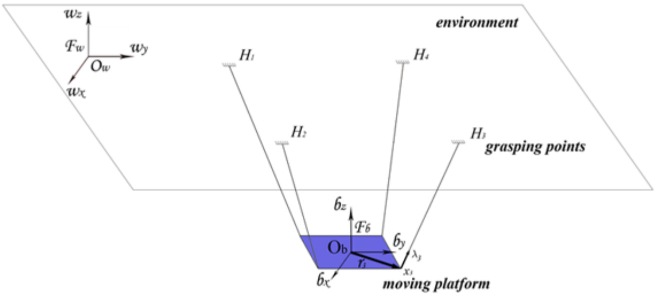

Fig. 3. The coordinate system of the robot.

Therefore:

$$\begin{bmatrix} w_x \\ w_y \\ w_z \end{bmatrix} = R(\psi, \theta, \phi) \begin{bmatrix} b_x \\ b_y \\ b_z \end{bmatrix} \tag{1}$$

The position of the i_{th} dispensing point in the fixed world coordinate system is a simple rigid body transformation.

$$x_i = Rr_i + d \tag{2}$$

where i indicates the number of the dispensing point. The four or three cables are in contact with the surrounding at points H_i. Then, the vectors describing the cables' lenghts are:

$$l_i = H_i - x_i \tag{3}$$

and a unit vector along the i_{th} cable is defined as:

$$\lambda_i = \frac{H_i - x_i}{\|H_i - x_i\|} = \frac{l_i}{\|l_i\|} \tag{4}$$

The tension force of the i_{th} cable can be expressed as $T_i = t_i \lambda_i$, where t_i is the magnitude of the force. In order for the moving platform to be at equilibrium configuration the sum of forces and torques are required to be zero. Next, we define the Jacobian of a robot with n cables as $J = \begin{bmatrix} J_1 & J_2 & \cdots & J_n \end{bmatrix} \in \mathbb{R}^{6\times n}$, where each column of J is defined as:

$$J_i = \begin{bmatrix} \lambda_i & Rr_i \times \lambda_i \end{bmatrix}^T, \tag{5}$$

and r_i is the vector from O_b to the i_{th} cable dispensing point represented at F_b coordinate system.

Let $F = \begin{bmatrix} f_1 & f_2 & f_3 & m_1 & m_2 & m_3 \end{bmatrix}^T$ represent the vector of external forces and torques applied on the moving platform. Let $\tau = \begin{bmatrix} t_1 & t_2 & \cdots & t_n \end{bmatrix}^T$ represent the vector of the magnitudes of cables tension forces. Then the equilibrium condition is: $F + J\tau = 0$. Since the Jacobian matrix is a position and orientation dependent matrix, the values of F depends on the tension of the cables, position and orientation of the moving platform. We are now ready to write the criterion for static equilibrium:

$$\begin{bmatrix} 0 \\ 0 \\ mg \\ 0_{3\times 1} \end{bmatrix} = \begin{bmatrix} \lambda_i & \dots & \lambda_n \\ Rr_1 \times \lambda_1 & \dots & Rr_n \times \lambda_n \end{bmatrix} \begin{bmatrix} t_1 \\ \vdots \\ t_n \end{bmatrix} \tag{6}$$

where m is the mass of the robot and g is the acceleration of gravity. In order to find the equilibrium configuration, the kinematic and static equations need to be solved simultaneously.

IV. Motion Planning

In this section we present the motion planning algorithm based on convex optimization. As mentioned before, motion is composed of two phases. First, internal motion inside the stance space during the stance phase, and second, relocation of the grasping points during the stride phase. Gaits are classified into quasi-static or dynamic, depending on the strategy used. The strategy chosen is related to the required speed, as slower walking gaits, i.e. creeping gaits, are generally quasi-static, whereas faster gaits are dynamic. Quasi-static gaits remain at equilibrium by relying on the support polygon formed by the cables in contact. In a quasi-static gait, the vertical projection of the center of gravity onto a horizontal plane is kept within the support polygon at all times [17]. In the absence of any inertial or external forces, and if the environment is sufficiently rigid, the robot can remain stable, as long as the center of gravity is within the support area.

For legged robots, where contact with the surounding is at individual points, a necessary condition for stability is that the robot has at least three legs on the ground at all times. In our case we require that the robot is connected by three cables. This is necessary in order to form an area of support that can contain the projection of the center of gravity within its borders (Fig. 4). The borders are the minimum convex hull point set in the support plane, such that all of the contact points are contained in the convex hull. It is clear that when m cables are in contact, the support pattern is a polygon of not more than m edges. Quasi-static gaits are generally quite slow, but the advantage is that they can be executed arbitrarily slow or even stop while being at equilibrium at all times. The motion planning is based on the assumption that we know the location of the center of mass which is the origan of F_b (Figure 3).

We will obtain optimal grasping points using convex optimization. In order for an optimization problem to be a convex one, the objective and constraint functions of the problem have to be convex. The objective function in this case is the sum of tensions of the cables and the constraint functions are equilibrium. In the case of a robot with six cables we can determine the position and orientation of the moving platform because the robot has six actuators (one for each cables). We do not need to insert the kinematic constrains to the problem but only the static constraints which are linear, and therefore are convex.

We find optimal grasping points by minimizing the tension on the cables. We start by finding the optimal grasping points for the initial position. After contact is established and the moving platform changes its position, we seek again for optimal grasping points while taking into account the current grasping points. In addition we are interested in minimizing the number of new contact points along a given path. We minimize the number of new contact points by increasing

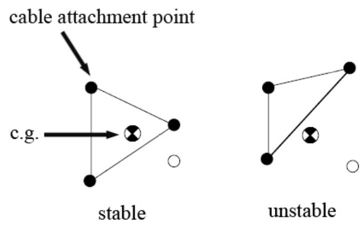

Fig. 4. Support polygon, statically stable and unstable cases. The filled dots represent cables that are attached to the surrounding and support the robot.

the weight of the current ones. In order to find the optimal grasping points we dispense from each dispensing point of the moving platform four cables. The four contact points generate a convex hull. We minimize the sum of all cable tensions, and then find a single cable from each corner, which is the average vector of the four optimal tension vectors. The four grasping points from each corner are chosen such that two are at a distance R_{in} from the corner of the moving platform. We determine R_{in} such that the stance space consents our workspace requirements. The other two grasping points are at a distance R_{out} from the same corner of the moving platform (Fig. 5). R_{out} is determined by the maximum cable length. The moving platform consists of seven vertices, where the distances between two corners are minimal in order to avoid singularity, as proven by [18]. In the case of four cables we cannot determine the orientation of the moving platform, and therefore we have to calculate the kinematic expressions by inserting them as constraints, however those expressions are not convex. We formulate the seven cable optimization problem as follows:

$$\begin{aligned} \text{minimize} \quad & \sum_{i=1}^{7}\left(\left\|\sum_{j=1}^{4} t_{ij}\lambda_{ij}\right\|_2 + \alpha\left\|t_{i5}\lambda_{i5}\right\|_2\right) \qquad (7)\\ \text{subject to} \quad & AT - B = 0_{6\times1}\\ & t_{ij} \geq 0 \end{aligned}$$

where

$$A_{ij} = \begin{bmatrix}\lambda_{ij}\\ M_{ij}\end{bmatrix}_{1\times6} \qquad B = \begin{bmatrix}0\\0\\mg\\0_{3\times1}\end{bmatrix}$$

$$M_{ij} = \left[x_i - cm\right] \times \lambda_{ij}$$

and

$$T = \begin{bmatrix}t_{11} & t_{12} & \dots & t_{14} & t_{21} & \dots & t_{74}\end{bmatrix}^T_{28\times1}$$
$$A = \begin{bmatrix}A_{11} & A_{12} & \dots & A_{14} & A_{21} & \dots & A_{74}\end{bmatrix}_{6\times28}$$

λ_{ij} represents a unit vector in the direction of the j_{th} cable from the i_{th} corner of the moving platform (Fig. 6). M_{ij} represents the moment of the j_{th} cable from the i_{th} corner of the moving platform with respect to the center of mass (cm). x_i represents the i_{th} vertices of the moving platform in F_w coordinate system. We denote the weight of the the previous configuration by α, where the subscript 5 in Eq. (7) represents the previous configuration. Thus t_{i5} represents the optimal previous tension and λ_{i5} represents a unit vector respectively. In order to minimize new grasping points, α needs to be less than one. If α is larger than one, the weight of the previous grasping points decreases because the objective function minimizes the sum of tensions. While at the initialization step $\alpha = 0$ and then $0 < \alpha < 1$. In case the optimal solution exceeds a single cable from a single corner, we calculate the average vector of those cables and find a single cable which is a linear combination of the optimal cables.

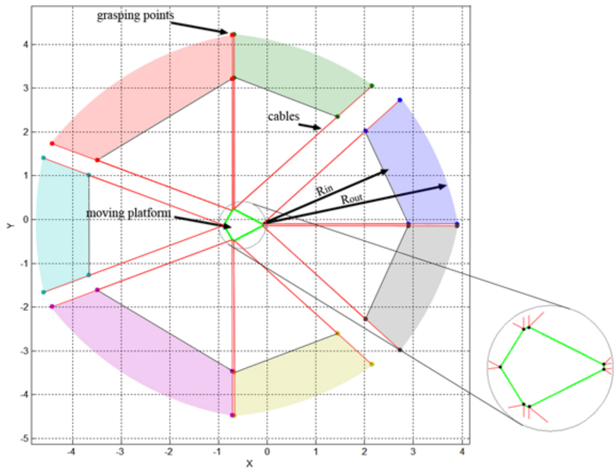

Fig. 5. The colored areas represent the convex hull that are obtained from the contact points. The red lines represent the cables before the optimization problem is solved.

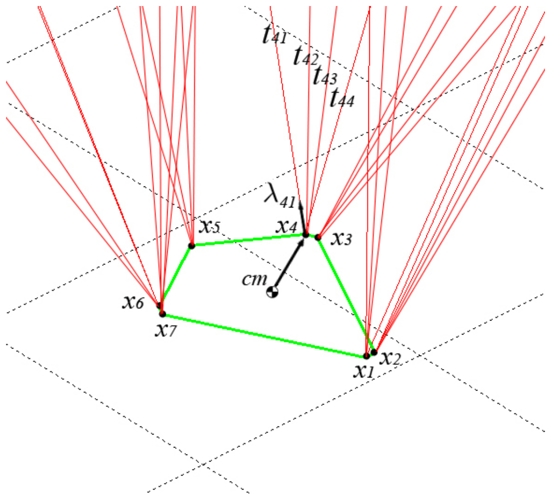

Fig. 6. A close up of the moving platform, the red lines represent the cables before the optimization problem is solved.

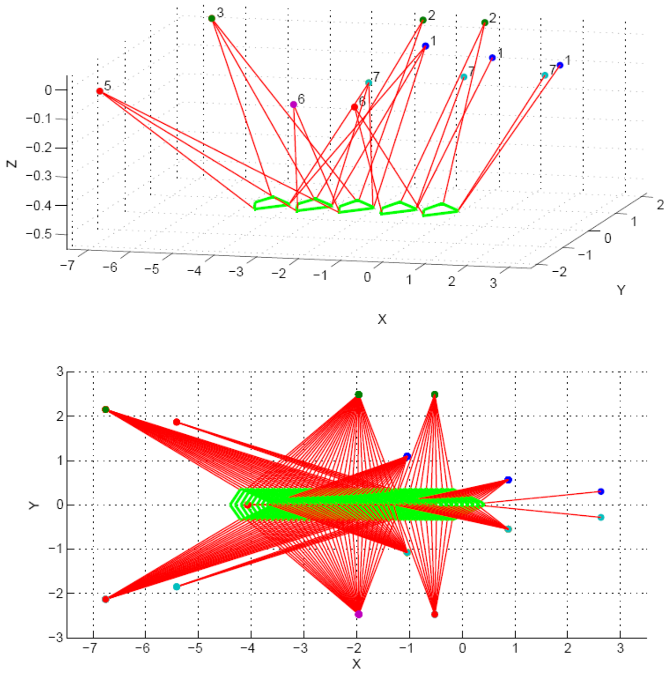

Fig. 7. Motion along the path $y = 0$ while implying the convex optimization problem. The upper figure displays progress every ten iterations while the lower figure shows each iteration on top of each other.

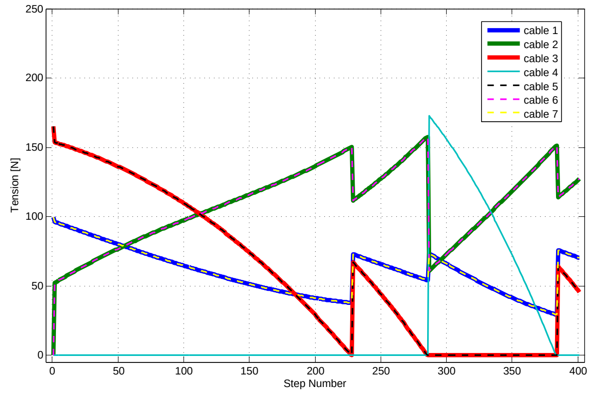

Fig. 8. Tension of each cable along the path $y = 0$. It can be seen that when cable three and five decrease their tension, cables two and six increase their tension.

V. Simulations and Experimental Results

Simulations were performed on a seven cable SpiderBot using the convex optimization algorithm. The solution of the convex optimization problem yields new grasping points. Fig. 7 represents motion along a given straight line in which $y = 0$ from $x = -4$ to $x = 0$ while applying the algorithm. The number of new grasping points does not exceed six. Applying the problem on a six cable SpiderBot yields the results presented in Fig. 8. The figure presents the tension of each of the cables that are connected to each corner. It can be seen that the number of cables connecting the moving platform does not exceed six at each step along the path. Furthermore it can be seen that while the robot moves along the path from left to right, the tension of cables three and five decrease, while the tension of cables two and six increase.

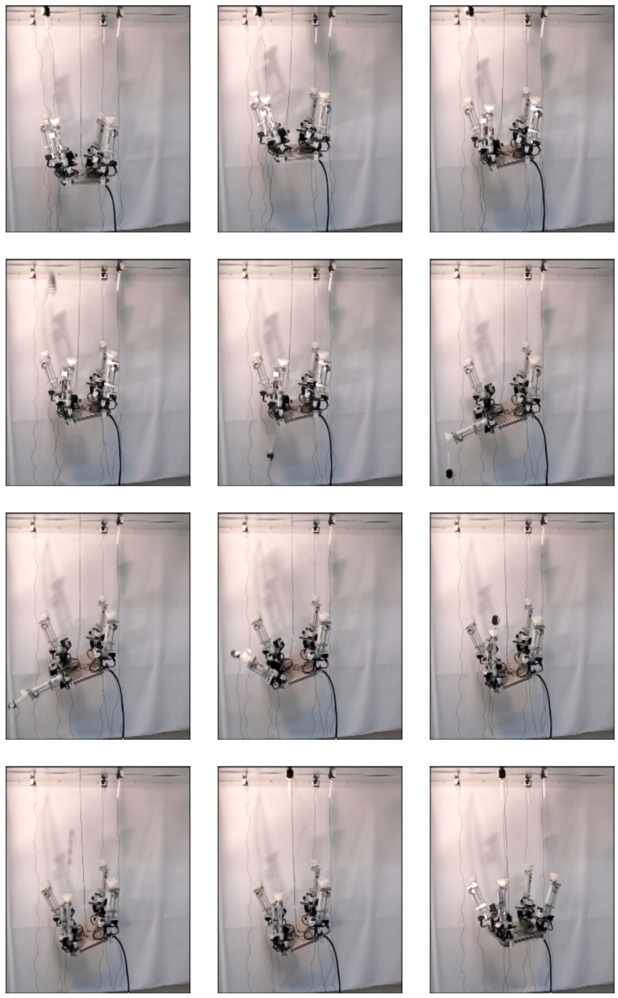

Fig. 9. SpiderBot performing one motion sequence while moving from one stance space to another.

In order to test the feasibility of the concept, a sequence of several mechanisms had to be tested. Fig. 9 presents screen shots of an integrated experiment. The first step is motion inside the stance space by rolling the cables on the sheaves. The next step is releasing one of the attached cables using the release mechanism at the end of the gripper. Then the gripper is rolled back to the cables mechanism in order to reconnect the griper to a new grasping point. After contact is established, motion inside the stance space is again performed.

VI. Conclusions

An automatic motion planning algorithm for a mobile robot suspended by seven cables was presented. The robot consists of a central body and seven cable mechanisms. The robot maintains contacts at six points, using six cable mechanisms, while obtaining a new contact point with the surroundings with the seventh mechanism. The robots' motion is based on changing its internal configuration by controlling the cables' lengths and selecting a new contact point towards the target configuration. A method to compute

the desired cable lengths during motion was presented. We also presented an algorithm for motion planning from one stance space to another. A motion planning algorithm was presented for a seven cable SpiderBot using convex optimization. We compute the optimal grasping point that reduces the sum of tensions on the cables and reduce the number of new contact points needed in order to perform stable motion along a desired path.

Further experiments will be conducted in order to test the motion algorithm more intensively. A seven cable SpiderBot will be built in order to test the convex optimization results and verify the theory presented in this work. A more advanced controller should be developed instead of the PID controller which is currently used. . Different surroundings will be tested(not just metalized environments) such as concrete and wood environments. Different grippers will need to be designed and built for the robot in order for it to cope with the different environments. A video showing the experiments and the motion of the robot can be found on our web site:

http://www.bgu.ac.il/∽ashapiro/media/spiderbot.wmv

References

[1] P. Bosscher, T. Andrew, and E. Imme, "Wrench-feasible work space generation for cable-driven robots," *IEEE Transactions on Robotics*, vol. 22, 2006.

[2] A. Capua, A. Shapiro, and S. Shoval, "Motion analysis of an underconstrained cable suspended mobile robot," *International Conference on Robotics and Biomimetics*, 2009.

[3] S. E. Landsberger and T. B. Sheridan, "A new design for parallel link manipulators," in *Proceedings of Sys. Man. and Cybernetics Conf., Tucson, AZ*, 1985,812-814.

[4] J. Albus, R. Bostelman, and N. Dagalakis, "The nist robocrane," *Journal of Robotic Systems*, pp. 709–724, 1993.

[5] R. Bostelman, A.Jacoff, and R.Bunch, "Delivery of an advanced double-hull ship welding system using robocrane," in *3rd International Computer Science Conventions Symposia on Intelligent Industrial Automation and Soft Computing Genova, Italy.*, 1999.

[6] T. Arai, K. Cleary, K. Homma, H. Adachi, and T. Nakamura, "Development of parallel link manipulator for underground excavation task," in *International Symposium on Advanced Robot Technology*, 1991.

[7] *August Design, "SkyCam", www.august design.com*.

[8] *August Design, "Intelligent spreader bar", www.august design.com*.

[9] A. Alp and S. Agrawal, "Cable suspended robot: Design, planing and control," in *IEEE International Conference on Robotics & Automation*, 2002.

[10] S. K. Agrawal, "Workspace boundaries of in-parallel manipulator systems," *International Journal of Robotics and Automation*, vol. 7, pp. 94–99.

[11] A. Fattah and S. K. Agrawal, "Design of cable-suspended planar parallel robots for an optimal workspace," in *Proceedings of the Workshop on Fundamental Issues and Future Research Directions for Parallel Mechanisms and Manipulators*, 2002.

[12] N. Yanai, M. Yamamoto, and A. Mohri, "Anti-sway control for wiresuspended mechanism based on dynamics compensation," in *Proceedings of the 2002 IEEE International Conference on Robotics and Automation*, 2002.

[13] A. B. Alp and S. K. Agrawal, "Cable suspended robots: Design, planning and control," in *Proceedings of the 2002 IEEE International Conference on Robotics and Automation*, 2002.

[14] A. Capua, "Motion analysis of an underconstraind cable suspended mobile robot," Master's thesis, Ben Gurion University of the Negev, 2009.

[15] E. Rimon, S. Shoval, and A. Shapiro, "Design of a spider robot for motion with quasistatic force constraints," *Journal of Autonomous Robots*, vol. 101, pp. 279–296, 2001.

[16] F. Reuleaux, "The kinematics of machinery:," *Macmillan*, 1876.

[17] R. B. McGhee and A. A. Frank, "On the stability properties of quadruped creeping gaits," *Mathematical Biosciences*, 1968.

[18] J. Pusey, A. Fattah, S. Agrawal, E. Messina, and A. Jacoff, "Design and workspace analysis of a 6-6 cable-suspended parallel robot," *Mechanism and Machine Theory*, 2004.